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13. ABSTRACT (Maximum 200 words)

The functional relationship between cloud cover and relative humidity (Rh) averaged over areas comparable to grid dimensions of numerical weather models was quantified using RTNEPH and 3DNEPH observations. Cloud cover in any atmospheric level decreases exponentially as layer-averaged Rh falls below 100%, and no observations support "critical Rhs" below which cloud cover is zero. Small cloud amounts occur at all Rhs. Therefore, current weather models probably underestimate cloud coverage, especially at Rhs below the "critical" humidities used by most models. At the same Rh, convection enhances cloud coverage in the upper troposphere, and decreases cloud coverage in the lower troposphere. Student Robert Iacovazzi developed a simplified and innovative mass-flux convective parameterization that was evaluated using atmospheric radon profiles, and was also used to simulate the redistribution of heat and moisture by combining the approach of stochastic mixing with detraining plumes. A public-domain cloud resolving model (ARPS) was used to further refine the 1-D parameterization. Both the cloud resolving models and the convective parameterization were evaluated using GATE observations. However the ARPS model employs an advection algorithm that does not conserve water mass, making it unreliable to use for refining cloud parameterizations.

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Final Technical Report

Improved Representations of Cloud-scale Processes in meteorological forecast models

Air Force Office of Scientific Research Grant # F49620-93-1-0392

July 1993 - June 1997

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31 July 1997

Project Goals: The primary goals of this research effort were to study and improve cloud and convective parameterizations used by meteorology models under the hypothesis that simplified numerical representations of clouds may introduce considerable uncertainties in weather forecasts. To achieve this goal, we used the Air Force 3DNEPH and RTNEPH cloud archives to examine the relationships between standard meteorology parameters and cloud cover, and we developed and tested an innovative convective parameterization that treats clouds as detraining ensembles of buoyant plumes, conveying mass from the lower troposphere to the middle and upper troposphere. These parameterizations allow for an improved numerical treatment of microphysical processes in meteorology models. Cloud cover and convective parameterizations were tested against Air Force cloud cover observations and GATE tropical observations. A sophisticated, two dimensional cloud-resolving model was used to further refine and evaluate the convection parameterization.

1. Abstract of Research findings: AASERT student augmentation: 7/93 - 6/97

During this 4-year research effort, graduate student Robert Iacovazzi (Bob) was trained in the area of cloud parameterization within numerical meteorology models. During the early years, Bob performed an extensive review of cumulus parameterization literature and developed a simplified and innovative 1-dimensional model that was tuned to atmospheric radon profiles. Radon is an ideal tracer of convective motions since it is emitted at the Earth's surface, and decays with a 5.5 day e-folding time, long enough so that an appreciable vertical gradient of this tracer is usually present in the atmosphere, but the gradient is strongly regulated by the intensity of primarily convective mixing in the middle and upper troposphere. During the middle of this research effort, the convective mixing model was extended to treat redistribution of heat and moisture by combining the approach of stochastic mixing (Raymond and Blyth, 1986) with detraining plumes (Walcek et al., 1994). At this phase, Bob obtained and began testing two multi-dimensional cloud resolving models (Aleksic et al., 1992; and the ARPS model [Xue et al., 1995]) for use as tools in further refining the 1-D parameterization. Both the cloud resolving models and the convective parameterization were initially tested using GATE Phase III convective observations. Bob passed his Ph. D. qualifying examination, and prepared a thesis proposal that

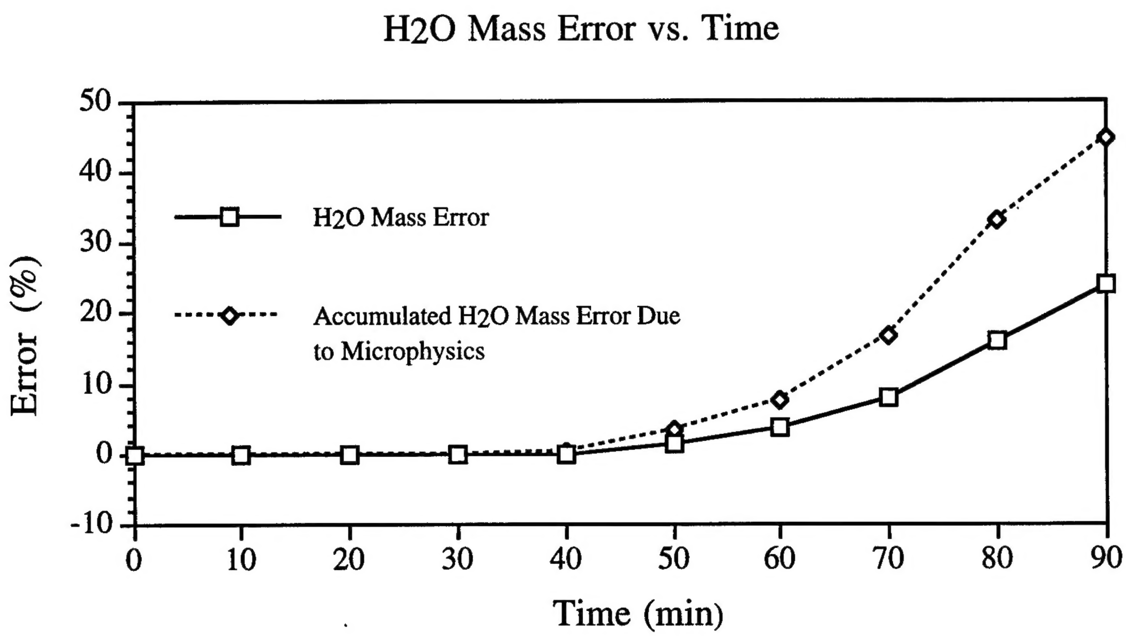

Fig. 1: Water mass error during a simulation of a hot bubble in a conditionally unstable environment using the ARPS (Xue et al., 1995) convective cloud model. At end of 1 1/2 hours, total water mass in the domain is higher by ~20%, primarily due to incorrect advection of falling precipitation.

was submitted and approved by a dissertation committee of five faculty members of the Department of Atmospheric Sciences in 1996. Unfortunately both high-resolution cloud models that Bob was planning to use for his research efforts were found to employ advection algorithms that did not conserve water mass, as shown in Fig. 1. Therefore these modeling tools were deemed unreliable to use as tools to further refine a simplified convective parameterization, for which mass conservation is essential. Removing these errors from the models would entail considerable time and efforts that would not further the goals of his Ph. D. During the frustrating phases of discovering these problems with public-domain cloud models, Bob received a professional job offer from a NASA research contractor, and for a combination of personal and professional reasons, Bob accepted the professional research position, postponing the progress towards the completion of his Ph. D. indefinitely.

The findings of this research effort complement the original parent Air Force research project. The goal of the parent award was to utilize satellite and surface-derived cloud observations together with standard meteorological measurements to evaluate and improve our ability to accurately diagnose and forecast cloud coverage. A major finding of this research effort was a

determination of the **functional relationship between cloud cover and relative humidity**. Cloud cover in any atmospheric level decreases exponentially as the layer-averaged relative humidity falls below 100%. This study provides one of the few observationally-derived functional relationships for estimating cloud cover from relative humidity. Previous assumed relationships were based largely on ad hoc assumptions or extremely sparse observations, and thus varied widely from simple "step function", on/off formulations, to more elaborate linear or quadratic approximations. Nearly all previous cloud cover algorithms assume that mesoscale cloud cover disappeared when relative humidities fell below "critical relative humidities" in the 60-90% range. We found no observational support for this assumption, and our findings suggest that small cloud amounts occur at nearly all relative humidities. These results suggest that current meteorology and climate models probably underestimate the presence of clouds, especially at humidities below the "critical" humidities used by most models.

We also discovered that for the same relative humidities, convection tends to enhance cloud coverage in the upper troposphere, and decrease cloud coverage in the lower troposphere presumably due to the effects of cumulus-induced subsidence. We have developed an **innovative mass-flux convective parameterization** for calculating convective tendencies of heat and moisture to quantify the influence of convection on cloud cover. This work was initiated under sponsorship of this grant, and continues with support from an AASERT augmentation award and other granting agencies.

2. Project summary

As part of the modeling efforts that have been successfully accomplished, a paper concerning the regulation of convective activity by mid-tropospheric relative humidity has been written for, and was presented at the 12th International Conference on Clouds and Precipitation (Aleksic *et. al.*, 1996). In this paper, it is discovered that significantly lowering relative humidity in the initial sounding above the surface layer can severely attenuate convective response, as shown in Fig. 2, which shows the redistribution of a water-like tracer within one convective "bubble" in a conditionally unstable environment typical of the tropical Atlantic (GATE). This figure was

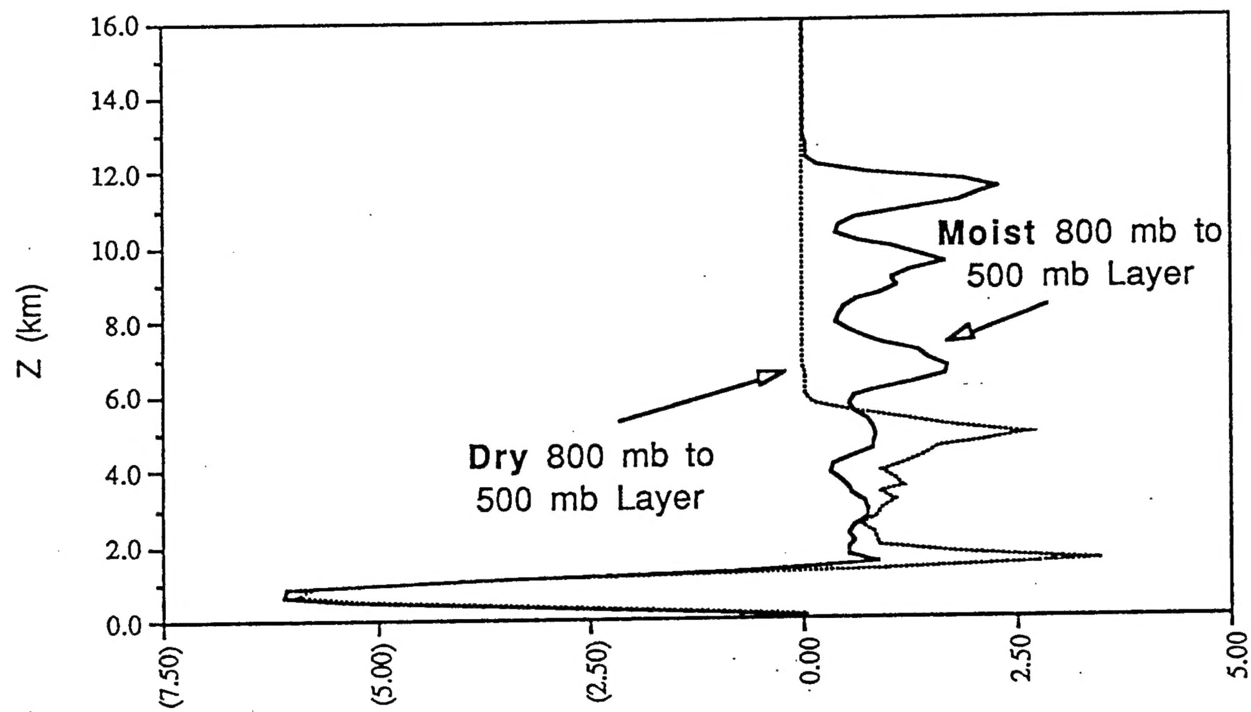

Figure 2: Two-hour, horizontal-domain-average concentration changes of an inert tracer that is assigned a non-zero value at the beginning of model simulations only inside of the initialized convective bubble, which is 2 km deep and centered at .8 km. In these two cases, the convective cloud grows into a moist (solid curve) and dry (dotted curve) atmosphere.

generated by using either the observed atmospheric humidity profile, where the Rh averaged in the layer from 800 - 500 mb was about 80%, and another simulation where the initial Rh in this layer was reduced to 50%. It is clearly evident that mid-tropospheric Rh strongly regulates convective mixing, but the converse also is shown: that convection strongly influences the Rh of the middle and upper troposphere.

As an extension to the preliminary research described above, Bob began investigating the attenuation of simulated convection in terms of parameters characterizing the states of the ambient environment and convective updrafts. Parameters associated with the ambient environment include convective available potential energy (CAPE), bulk Richardson number, mid-tropospheric subsaturation mixing ratio, and vertical wind shear. Properties of cumulus updrafts considered include average buoyancy, turbulence energy, and vertical velocity. The attenuation of simulated convective activity can be characterized in a simple 1-D parameterization using a fractional detrainment of undiluted cumulus mass flux described by Walcek *et. al.* (1994). It is hoped that a high-resolution explicit cloud model could provide a more empirical definition of undiluted cumulus mass flux fractional detrainment, which in turn can be used to make the cumulus parameterization more flexible and accurate.

Using GATE observations, the relationship between convective intensity and CAPE or mid-tropospheric average subsaturation mixing ratio and vertical wind shear in GATE Phase III was extensively explored. This study was initiated with the observation that considerable changes of convective intensity are found in the GATE Phase III dataset, even though these same data indicate that CAPE is always greater than 1100 J/kg and vertical temperature structure remains nearly unchanged. With research, it has been discovered that mid-tropospheric average subsaturation mixing ratio and vertical wind shear can be used together with CAPE to predict GATE Phase III convective intensity during periods when the data indicate a diminutive atmospheric capacity to organize convective. This results is shown in Figure 3, where rainfall rate and convective penetration factor (CPF), a parameter inversely related to a product of mid-tropospheric average subsaturation mixing ratio and vertical wind shear, have a linear correlation

coefficient of ~0.74 for cases when the GATE Phase III data are characterized by above median bulk Richardson number. Also found in this study is that, when precipitation rate data are segregated into median-divided subregions of CAPE and CPF parameter space, then averaged in each subregion, two major convective intensity regimes become evident: 1) a regime of relatively weak convective intensity associated with above median CAPE and below median CPF values; and 2) a regime of relatively strong convective intensity associated with below median CAPE and above median CPF values. This is shown in Figure 4. Also, with evidence from two simple case studies of convective outbreaks, the occurrence of these two major convective regimes in the GATE Phase III region is attributed to regulation of the magnitude of CAPE, which arises in response to opposing lower-tropospheric, convection-driven and surface-based, evaporation-driven moisture fluxes.

Results of the final stages of this research effort have been summarized in publications that are a part of the Forth International Cloud Modeling Workshop (organized by the WMO) and the 12th International Conference on Clouds and Precipitation (publications attached as an appendix to this report). At the cloud modeling workshop, the cloud resolving model was used to simulate the formation of intense precipitation and hail in Colorado. The results of our cloud models were compared and contrasted with other cloud models, and results of all cloud models was compared with several convective parameterizations.

3. Presentations and publications partially supported by this AFOSR:

In past annual progress reports, hard copies of all of these papers have been provided. Here only the papers appearing in the final year of the research effort are included with this report. If the reader is interested in obtaining hard copies of any of the papers below, please contact the project PI (address & phone on report face page).

Aleksic, N. M., R. A. Iacovazzi, C. J. Walcek and B. T. Telenta 1996: Regulation of convective activity by mid-tropospheric relative humidity: interactions between turbulence, microphysics and larger-scale convective dynamics. Proceedings, 12th International Conference on Clouds and Precipitation. Zurich, Switzerland 19-23 August 1996, 581-585

Iacovazzi, R. A., N. M. Aleksic and C. J. Walcek 1996: The 24 June 1992 Occurrence of heavy rain and hail in Colorado: a simulation using a fully compressible nonhydrostatic time-dependent two dimensional cloud model. WMO-sponsored Fourth International Cloud Modeling Workshop. 12 - 16 August 1996, Clermont-Ferrand, France.

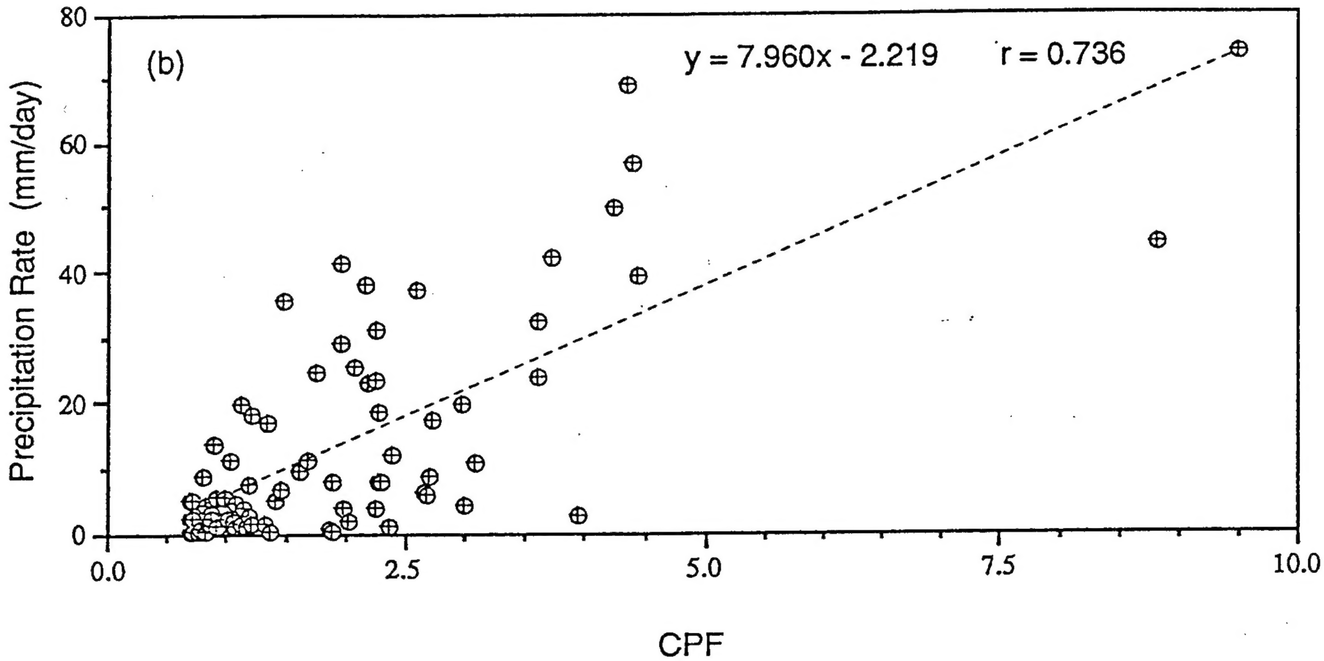

Figure 3: GATE Phase III precipitation rate data plotted versus convective penetration factor (CPF) for bulk Richardson number greater than the dataset median value of 219.4. The straight lines and their associated equations and correlation coefficients are products of linear regression analyses.

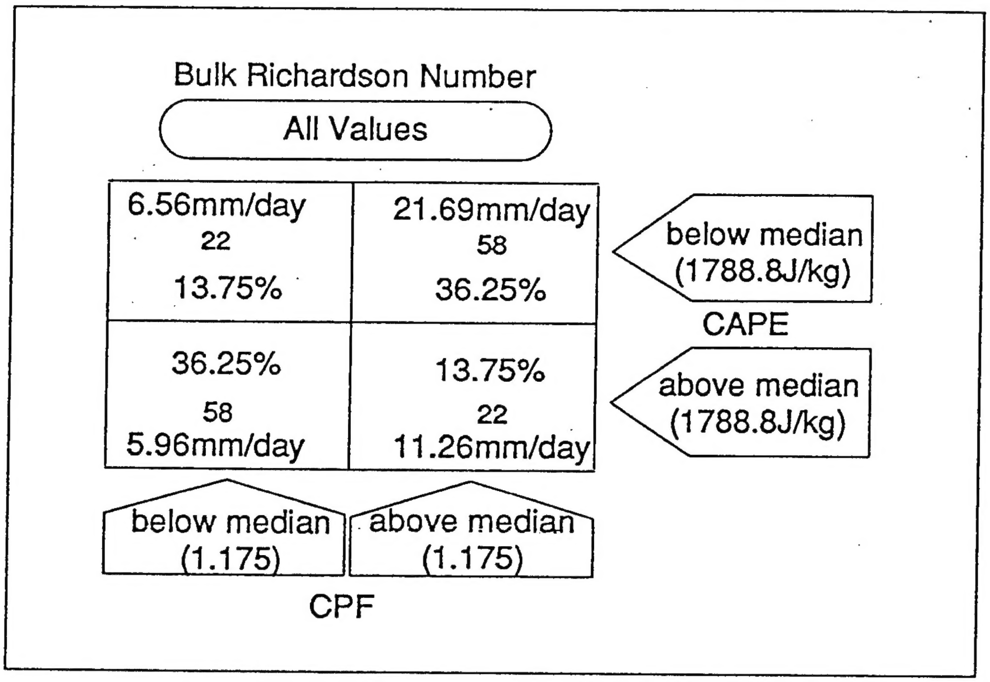

Figure 4: CAPE and CPF parameter space sub regions for for all GATE Phase III data. The sub regions are divided by CAPE and CPF medians of 1788.8 J/kg and 1.175, respectively. Within each sub region, the integer represents the number of GATE Phase III hour-average precipitation observations accounted for in the sub region and the precipitation rate is the sub region average. Also, the percent denotes the sub region percent frequency of observations.

Walcek, C. J., 1994: Cloud cover and its relationship with meteorological factors during a springtime midlatitude cyclone. ***Monthly Weather Review, 122,*** 1021-1035.

Walcek, C. J., 1995: Cloud Microphysics in GCM cumulus parameterizations: what ensemble averaged quantities really matter? *Conference on Cloud Physics*, Dallas, TX 15-20 January 1995. American Meteorological Society, 45 Beacon St., Boston, MA 02108, 381-382.

Walcek, C. J., 1993: Cloud cover and its relationship with meteorological factors during a springtime midlatitude cyclone. Cloud Impacts on DOD Operations and Systems 1993 Conference (CIDOS-93), Ft. Belvoir, VA, 16-19 November 1993. D. D. Grantham, Editor, Phillips Laboratory, Directorate of Geophysics, Hanscom Air Force Base, MA 01731-3010, 235-240.

Walcek, C. J., Q. Hu and B. Iacovazzi 1994: Cumulus clouds parameterized as detraining plumes. *10th Conference on Numerical Weather Prediction*, Portland, OR 18-22 July 1994. American Meteorological Society, 45 Beacon St., Boston, MA 02108, 77-78.

Walcek, C. J., and Q. Hu 1993: A cumulus parameterization scheme of detraining drafts, *20th Conference on Hurricanes and Tropical Meteorology* San Antonio, TX, 10-14 May 1993. American Meteorological Society, Boston, MA. 345-348.

Walcek, C. J., 1993: Factors influencing regional-scale cloud cover: Investigations using satellite-derived cloud cover and standard meteorological observations. *Fourth Symposium on Global Change Studies*, Anaheim, CA 17-22 January 1993. American Meteorological Society, 45 Beacon St., Boston, MA 02108, 235-236.

Walcek, C. J., 1992: Cloud cover and its relationship with relative humidity during a springtime midlatitude cyclone: some implications for climate models. Proceedings, 11th International Conference on Clouds and Precipitation. Montreal, Canada, 17-21 August 1992. Elsevier Publishers, 1128-1131.

Walcek, C. J., 1992: Extrapolating cloud-scale microphysical, dynamic, and radiative processes to global and climatic scales: How accurately do we know the fractional area of cloud coverage?. Workshop proceedings of the WMO Cloud Microphysics and Applications to Global Climate Change Workshop. Toronto, Canada, 10-14 August 1992.

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Aleksic, N. M., R. A. Iacovazzi, C. J. Walcek and B. T. Telenta 1996: Regulation of convective activity by mid-tropospheric relative humidity: interactions between turbulence, microphysics and larger-scale convective dynamics. Proceedings, 12th International Conference on Clouds and Precipitation. Zurich, Switzerland 19-23 August 1996, 581-585

Aleksic, N. M., B. Telenta, and S. Petkovic, 1992: Seeding repeat rates for direct injection seeding by rockets. *J. Wea. Mod.*, 24, 84-88.

Raymond, D. J. and A. M. Blyth, 1986: A stochastic mixing model for nonprecipitating cumulus clouds. *J. Atmos. Sci.*, 43, 2708-2718.

Walcek, C. J., Q. Hu, and B. Iacovazzi, 1994: Cumulus clouds parameterized as detraining plumes. *Proc. of the Tenth Conference on Numerical Weather Prediction,* Portland, Amer. Meteor. Soc., 77-78.

Xue, M., K. K. Droegemeier, V. Wong, A. Shapiro, K. Brewster, 1995: ARPS, Advanced Regional Prediction System, version 4 users guide. Center for analysis and prediction of storms, University of Oklahoma, Norman, OK.

APPENDIX:

copies of two publications of research results